



OIL CORROSION AND CONDUCTING Cu_2S DEPOSITION IN POWER TRANSFORMER WINDINGS

CLAES BENGTTSSON¹, MATS DAHLUND¹, JAN HAJEK¹,
LARS F PETTERSSON¹, KARIN GUSTAFSSON²,
ROBERT LEANDERSSON², ARNE HJORTSBERG³

¹ ABB Power Technologies AB, Ludvika
Sweden

² ABB Corporate Research, Västerås
Sweden

³ ABB Corporate Research, Baden
Switzerland

SUMMARY

Copper corrosion and Cu_2S deposition, has recently led to failures of transformers & shunt reactors during service. Units from several different operators and several OEMs have been affected. Analysis of actual failure cases showed that these transformers were well within established industry standard practice regarding design as well as operation, and used oil that fulfilled international material standards. Sealed units with rubber sack appear primarily to have been affected.

Final failure has occurred as a turn-to-turn breakdown in the HV windings, and inspection of the failed windings showed deposits in the winding consisting of Cuprous Sulphide, Cu_2S , an electrically conducting compound. The deposits varied within the winding, usually with more deposits in the upper part of the windings, but the complex deposition pattern could not be explained simply by the temperature distribution.

We have carried out comprehensive corrosion research aiming at a thorough understanding of the phenomenon, and have reproduced the corrosion as well as the deposition of Cu_2S in our laboratories. The influence of the gas content of the oil, and other parameters have been studied under very well controlled circumstances, and a number of different oils have been evaluated at temperatures ranging from 80 to 150 °C.

The main finding is that Cu_2S deposition occurs only for certain oils, which can cause corrosion and deposition under the typical environment of a sealed power transformer. With such oils deposition has been demonstrated over a wide temperatures range, from as low as 80 °C, and on a variety of solid materials. These oils further show a very strong oxygen dependence of the deposition, which explains much of the observed complex deposition patterns in the failed units.

Real failures have all occurred with transformer oils that passed the corrosion tests in the international standards, DIN 51353 and ASTM D1275 respectively. Improved test methods are clearly needed that can take into account the observed oxygen dependence, an important factor present in real transformers.

A Covered Conductor Deposition (CCD) test has demonstrated a superior selectivity for identifying the corrosive oils that have caused actual failures in transformers, and is thus a very promising type of test.

KEYWORDS

Transformer oil, failure, corrosion, deposition, copper sulphide, Cu_2S

Introduction & background

The reliability of power transformers is normally quite high and the expected life time of transformers typically exceeds 30 years. Power transformers are crucial elements in all power networks and are considered particularly important due to the relatively long repair time of transformers. Recent observations of premature transformer failures in the field caused by Cu_2S deposition [1, 2, 3, 4, 5] has therefore raised a large interest in the power industry. Before this, corrosive transformer oils have not been a technical issue of any major significance in the power industry. Corrosion in transformer windings has been observed [6], and the topic was discussed in a few cases [7, 8] during the last decades, but the relatively few failure cases have been considered as singular events that did not lead to a detailed analysis of the real cause of the problem.

The recent set of failures however are different in the sense that there is a larger number of failed units, several different OEMs and utilities have been affected and the failures have occurred although the design, the operation as well as the materials used are well within established industry standards and established praxis [4,5]. Specifically all the oils used had originally passed the corrosion test in the IEC or ASTM standards. The present corrosion test go back to a time when the sulphur content of oils was typically orders of magnitude higher than the present levels [9,10]. The fact that these tests have not been able to screen out the oils causing Cu_2S deposition failures has led to a prompt response from CIGRE and IEC as well as ASTM to analyse and review the present testing standards [11,12,13].

In this paper we have reviewed the Cu_2S deposition failure findings, investigated the deposition mechanisms in detailed laboratory studies, and explored a new possible method for testing and evaluating transformer oils with respect to corrosion and deposition.

1 FAILURE INVESTIGATIONS

1.1 Transformer failure cases

The failure cases that have been reported recently all fall into three distinct categories: Shunt reactors, HVDC converter transformers, and Generator step-up transformers. These categories all typically have a high and relatively constant load. This means that the time-temperature integral is likely to be relatively high, a factor that would accelerate any temperature dependent chemical reaction like corrosion.

Most cases reported seem to have occurred in locations with a hot or at least seasonally hot climate. The relatively large number of failures reported from Brazil regarding 500 kV Shunt reactors [4] is a good example of such high load service in a warm climate. Transformer units delivered to warm climates are of course designed and cooled in such a way that the maximum allowed absolute temperatures are not exceeded, but the year average temperatures may still be higher in a hot climate where the ambient temperature is high

1.2 Overall analysis of design, manufacturing and operation of failed units

In several recent cases of transformer failures caused by Cu_2S deposition a careful analysis of the design, the manufacturing and the operation has been performed by manufacturers and operators in order to find any clues to the cause of the failures. Several such analyses from different suppliers have demonstrated [1, 4, 5] that the units had all been designed according to well established industry standard, and that no manufacturing errors could explain the failures. Similarly these investigations showed that the operation had been perfectly normal and well within accepted industry loading guides. Specifically several authors have demonstrated that corrosion has occurred although accepted temperature limits have not been exceeded [4, 5]. The common denominator found in these failure investigations [4] is that these transformers all used certain oils that seem to have caused the corrosive reactions, although all operational factors were normal.

1.3 General winding deposition observations

Several authors have recently described their findings in connection with analysis of units failing due to Cu_2S deposition in power transformer windings [1, 2, 3, 4, 5]. A very common picture has emerged of the deposition and its distribution in the windings.

Corrosion of the copper conductors is often revealed by a distinctive discoloration of the copper conductor surface. This colour can vary from various shades of red-blue-violet to green and graphite-black. Examples of such corrosion attack on the copper are shown in fig 1. These deposits are found to contain copper and sulphur, and cuprous sulphide, Cu_2S , has been identified with different techniques.

Similarly the deposits on the cellulose insulation facing the conductor also vary widely in colour and general appearance, and often have a shiny metallic lustre, and violet-blue-green tint as shown in fig 1. These deposits have also been shown to contain Cu_2S . Deposits can also sometimes be observed on several paper layers extending out from the copper conductor, in severe cases throughout the entire conductor insulation.



Fig 1. Corroded copper conductor (left) showing clear Cu_2S deposition on the wrapping paper. Right shows deposits on paper between spacers in disc winding. This type often also contains sludge.

Deposits have also been observed on the outside of the paper wrapping as shown in fig 1. In this case deposits are observed which sometimes appear more fundamentally different in type, with varying colours and general appearance but also with different chemical and electrical properties. A large variation in the electrical conductivity was observed, some with little or no conductivity at all, and others showing the typical conductivity of Cu_2S deposits. There is often a substantial amount of normal sludge in these deposits.

1.4 Observed deposition patterns in windings

Several authors have recently observed and analysed the deposition pattern in failed transformer windings in order to draw conclusions regarding the factors influencing the corrosion and deposition mechanisms [2, 4, 5, 14]. The following is observed:

1. Deposits directly on the copper conductor and the facing wrapping paper
 - a. is generally stronger in the upper part of winding, but not necessarily at the very top
 - b. varies across conductors turns in radial direction in a disc
 - c. can differ widely between adjacent conductors, or sides of the same conductor
 - d. can vary strongly along the conductor crossing a spacer in a disc winding
2. Deposits on the outside of conductor insulation and on spacers
 - a. is more prevalent on transformers with longer service time
 - b. is generally stronger in the upper part of winding, but not necessarily at the very top
 - c. varies across conductors turns in radial direction in a disc
 - d. can some times be strong between spacers and weak under spacers or vice versa
 - e. is observed also on outside of paper wrapped enamelled conductors
 - f. deposition often stronger in part of winding where oil flow estimated to be low
3. Deposition amount relation to winding temperature
 - a. maximum deposition not at highest temperature locations in windings
 - b. DP numbers of deposited paper often quite high at high deposition location

This complex deposition pattern suggests that several factors influence the chemical reactions responsible for the copper surface corrosion and subsequent formation of copper sulphide and other deposits on transformer insulation.

1.5 Cu_2S deposition pattern correlation to temperature and oil flow in windings

Several authors have noticed and commented on the apparent correlation of the observed deposition patterns and the assumed temperature distribution in windings. Can the temperature distribution alone explain the deposition pattern?



Fig 2. Examples of Cu_2S deposition on wrapping paper showing large difference in amount of deposition on the two sides of the conductor.

It is clear already by observing the large variation in deposits on conductors and the first paper layer that other factors than temperature has a large influence. As shown in fig 2 the two sides of the same conductor can have very different deposition although the temperature must be very similar.

In disc windings we have observed that the amount of deposition can sometimes vary drastically close to versus under a spacer, from low too high or from high to low, as shown in fig 3 below. In both cases the temperature is similar but somewhat higher under the spacer, since the oil has no access for cooling in this area. Clearly, other factors than temperature must play an important role for deposition here.



Fig.3. Examples of deposition between spacers left, and under spacer right

We conclude from our deposition observations that the corrosion and deposition processes are complex and depend on several factors in the environment. Temperature appear to be a general accelerating overall factor, but as shown by the above examples there are also other environmental factors that sometimes dominate over the effect of temperature.

1.6 Conclusions from winding analysis

Failures have occurred in Shunt reactors, GSUs and HVDC converter transformers, all operating at relatively high loads and many but not all in relatively warm environments. The cause of failure is formation of conducting cuprous sulphide deposits, which is accelerated by temperature. The deposition pattern in windings shows that also other factors influence the deposition pattern greatly. Hence the observed deposition pattern cannot be traced back to the temperature distribution only.

The root cause of the corrosion and subsequent deposition is certain corrosive oils.

2 CU₂S-DEPOSITION IN THE LABORATORY

2.1 Covered conductor deposition experimental set up

To investigate the cause of the deposition phenomenon, detailed laboratory studies have been performed. After a substantial variation of experimental parameters, the deposition of Cu₂S on the insulation has been reproduced in the laboratory. A flexible set-up was chosen, using IEC 61125 equipment, with a 3 cm long real copper conductor in a glass tube with 40 g oil. The conductor was wrapped in a few layers of insulation Kraft paper. A gas mixture can be bubbled through an inner glass tube to control the gas in oil content, in order to simulate the actual environment in a transformer as accurately as possible, and the temperature of the arrangement is conveniently controlled by an external thermostat. The complete set up for this Covered Conductor Deposition (CCD) test is shown in fig 4 below.



Fig 4. Laboratory experimental arrangement for Covered Conductor Deposition (CCD) test, and examples of Cu₂S deposition on Kraft paper

Many different combinations of experimental environmental factors have been investigated. The influence of the gas content of the oil, the type of wrapping material, the status of the metal surface, the temperature in the sample and other parameters have been studied under very well controlled circumstances. Many different oils have also been evaluated at temperatures from 80 up to 150 °C.

The major overall conclusion from these deposition experiments is that only certain oils do actually create Cu₂S deposition. These oils are also the very oils that have caused real transformer failures in the field as will be discussed in section 4 below. For oils which do create corrosion and deposition the influence of various environmental parameters has been studied. A very large number (> 1000) of samples have been studied. In order to facilitate a simple quantitative evaluation of the amount of deposition a deposition scale 0-10 has been defined, as shown in fig 5 below.

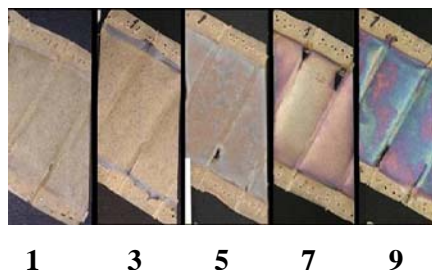


Fig.5. Scale for evaluation of CCD. 0 = no deposit, 5 thin covering of complete area, 10 very heavy deposition. This reading is used as a semi-quantitative measure of the amount of deposition.

2.2 Experimental simulation of real transformer environments

2.2.1 Effect of dissolved oxygen in the oil

In free breathing transformers the equilibrium oxygen content in the oil is approximately 30000 ppm, whereas in sealed transformers it typically varies from very low values of the order of 100 ppm, up to very high values of perhaps 20000 ppm, when air has had access for some reason. Normal operating

values for sealed units is typically a few thousand ppm oxygen. We have simulated the complete operating range by bubbling oxygen/nitrogen mixtures ranging from 0.0, 0.1, 0.5, 1, 2, 5, 10, to 20 % oxygen in the gas corresponding approximately to the range 0-30000 ppm oxygen in the oil.

When depositing oil is studied, very pronounced oxygen dependence can be observed as shown in fig.6 below for oil A. The amount of deposition on the paper increases dramatically as the amount of oxygen in the gas is increased from pure nitrogen. For the oil used in this case the amount of deposition has a maximum at approximately 2-3 % oxygen in the gas, corresponding to 3-5000 ppm in the oil, and then falls to a lower value at very high oxygen levels.

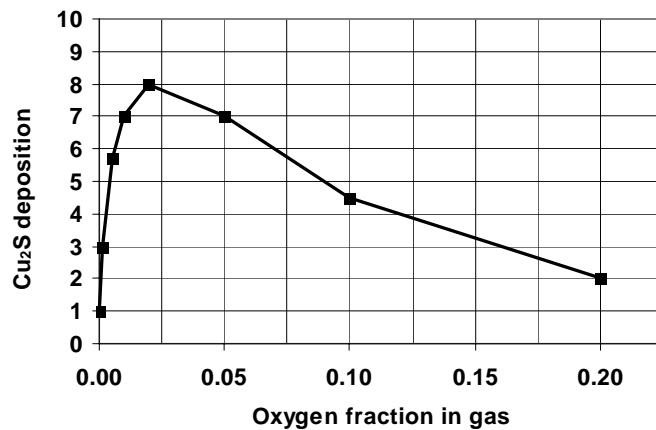


Fig 6. Relative deposition amount on Kraft paper in CCD test versus levels of oxygen in oil A. CCD- tests performed at 120°C for 32 days, 1 l/h of gas bubbled through oil.

The interval in which strong CCD-deposition occurs is clearly in the range of normal transformer operation for sealed units, while the high end corresponds to the typical oxygen levels of free breathing transformers. In a general way these data may also indicate that sealed units would be more at risk than free breathing units, at least for the oil under study here.

2.2.2 Temperature dependence of deposition

When sufficient oxygen is supplied to the CCD test the Cu₂S deposition is found to be thermally accelerated as expected. The rate of deposition is doubled after a 10°C increase, four times as high for 20°C etc. Figure 7 shows the amount of deposition after 8 days at 120°C and 32 days at 100°C with varying oxygen content in the gas for oil A. Evidently the deposits at each of these oxygen levels is approximately the same for the two series, i.e. 20°C temperature increase corresponds to a rate increase of approximately four times.

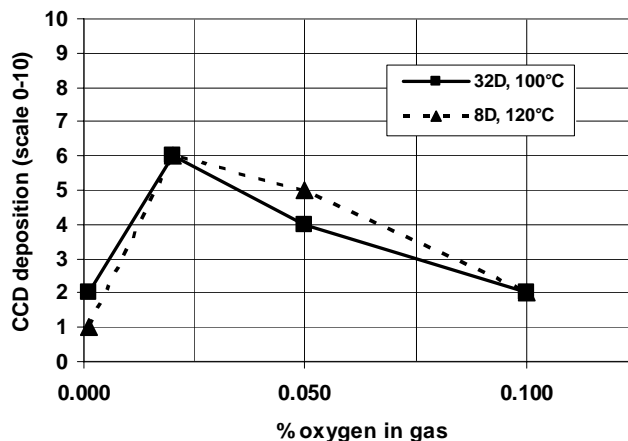


Fig 7. Relative deposition amount on Kraft paper in CCD test versus levels of oxygen in oil A. CCD- tests performed at 100°C for 32 days, and 120°C for 8 days, 1 l/h of gas bubbled through oil.

If a very much lower amount of oxygen is supplied in the test, we have observed that the temperature dependence of the Cu_2S deposition often appears different, and does not increase as expected with temperature. We attribute this to competition with other oil - oxygen reactions at elevated temperatures which deplete the oxygen needed for the chemical reactions involved in the corrosion and Cu_2S formation.

In a similar way, if the oxygen outlet is placed above the surface of the oil, so that the actual amount of oxygen in the oil has to be dissolved through the top oil surface, the equilibrium level of oxygen cannot be maintained in the oil at elevated temperatures since the oxidation of the oil competes with the corrosion and Cu_2S formation and depletes the oxygen necessary for these reactions. This effect was found to be particularly pronounced in uninhibited oils which consume much more oxygen.

2.2.3 Effect of wrapping material and moisture on Cu_2S formation

The CCD set-up has also been used to evaluate the influence of a number of other factors. Some authors have previously raised the possibility that the insulation paper itself may be the source of sulphur, and hence the oil would not be the cause [8]. Using the CCD test we have found that for depositing oils the same type of Cu_2S - deposits are formed on various materials like Nomex^R, conventional Kraft paper as well as thermally upgraded paper. This demonstrates that the basic corrosion and Cu_2S formation occurs on a range of material and does not require sulphur from other sources than the oil.

The effect of initial moisture in the wrapping paper has also been studied. We have compared Kraft paper with varying degree of initial moisture to completely dry paper in CCD tests. The results showed that there was no major difference between papers with different initial moisture levels.

2.3 Conclusions from laboratory results regarding real winding deposits

Laboratory deposition studies show that Cu_2S deposition occurs only with certain oils. For such oils the local oxygen level is a decisive factor for copper corrosion and Cu_2S deposition. The deposition increases rapidly from the oxygen free oil until a few 1000 ppm oxygen, and then remains strong up to perhaps 10000 ppm. At very high levels of oxygen, around 20- 30000 ppm, typical of free breathing transformers, the deposition appears to level off, at least in some oils.

Cu_2S deposition was found to be thermally accelerated, with the deposition rate approximately doubling for a 10°C temperature increase. The very strong sensitivity of the Cu_2S deposition to the local oxygen concentration provides a new factor to consider when the deposition pattern in failed transformer windings is analysed. Most such interpretations so far have assumed that variations observed have been the effect of temperature variations in the winding only.

The deposition patterns observed as described in section 2 show that there is a need for another factor to explain the observations. Our laboratory results indicate that local oxygen variations may be this missing factor. In transformers the local oxygen levels in the oil as well as in the paper and at the conductor surface does vary depending on the local oil flow speed, the thickness of the paper and spacers etc. The oxygen sensitivity of the deposition now makes it clear why the deposition pattern can be as complex as observed. Further, we need not interpret this complex pattern as being due to the temperature profile only, which as demonstrated in section 2 may lead to contradictions.

3 CORROSIVITY AND Cu_2S DEPOSITION TEST OF COMMERCIAL OILS.

One of the crucial issues regarding the recent Cu_2S deposition transformer failures is the fact that in all failure cases the oil used had previously tested non-corrosive according the standards used, either ASTM D1275 or IEC/DIN 51353. Since these methods have not been able to screen out unsuitable oils there is a need to develop more selective test methods. This issue has recently been addressed by CIGRE and IEC as well as ASTM [12, 13].

3.1 Evaluation of commercial transformer oils with extended ASTM test method

We have used 17 different new unused commercial transformer oils from different suppliers produced at various times during the last 15 years as a representative set of real transformer oils in use today. They vary widely in total sulphur content and many other characteristics, but they all fulfil the respective standards. These oils have all been tested with an extended version of the ASTM D1275 test, in which the time has been extended from 19 to 48 h, and the temperature raised from 140 to 150°C. For evaluation of the result, the pass/fail criterion from the D130 scale (range 1-4) has been applied, i.e. less than 4 means pass, 4 means fail or “corrosive”. This corresponds to a dark or grey surface deposition on the copper. The results of the selected group of oils are shown in Fig. 8 below.

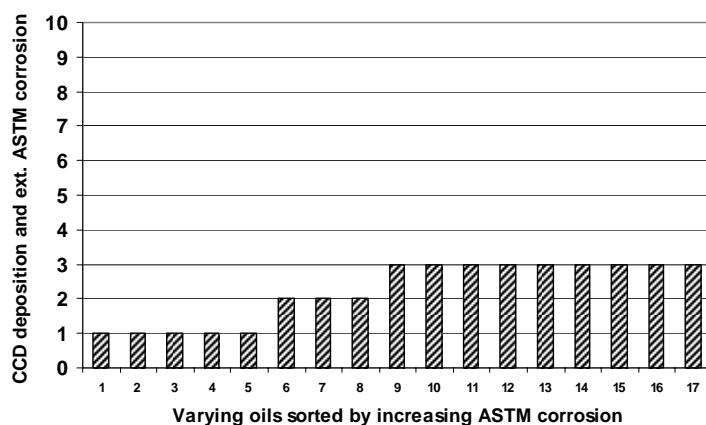


Fig. 8 Results of Extended ASTM D1275 corrosion tests for group of commercial oils

The results shows that all the oils tested here with the extended ASTM D1275 test actually did pass this tougher metal strip test, and hence also the standard ASTM D1275 test. We would accept all these oils, but would suspect oils 9-17 of be closer to being “corrosive”. However, since there is relatively little variation between the oils it is hard to define a natural more stringent fail/pass criterion.

3.2 CCD as a corrosion test method for transformer oils

The CCD experimental set up can also be used as a defined corrosion test method for transformer oils. Depending on the degree of acceleration needed tests can be run at different temperatures, and oxygen levels. We have investigated the use of this CCD set -up at temperatures from 100 to 150 °C, with oxygen levels in the gas from 0.5 to 2%. The results presented below have been obtained at 120°C for 14 days, 2% oxygen in nitrogen gas, 1.0 litre /h gas bubbling speed, and the copper wrapped in 2/3 layers of 0.060 mm Kraft paper. The scale defined above in fig. 5 has been used to quantify the results. Non-corrosive unused transformer oil should show essentially no Cu_2S - deposition in this test, whereas depositing oil should show a clear deposit. Hence the fail/pass criterion can be set to pass if the reading is “less than 1”.

3.2.1 Evaluation of commercial transformer oils with CCD test method

The same set of commercial oil samples have been tested and evaluated with CCD, showing a very good reproducibility. The results in Fig. 9 below show that there are large differences in Cu_2S - deposition between the different oils. Some oils show essentially no deposition. These oils also in most cases show no deposition even if the test is continued for longer time. Other oils have varying degree of deposition, in some cases extremely strong. If the pass/fail criterion is set to “less than 1”, oils number 5,7,13,16 and 17 have clearly failed this test clearly, while number 8 is on the borderline.

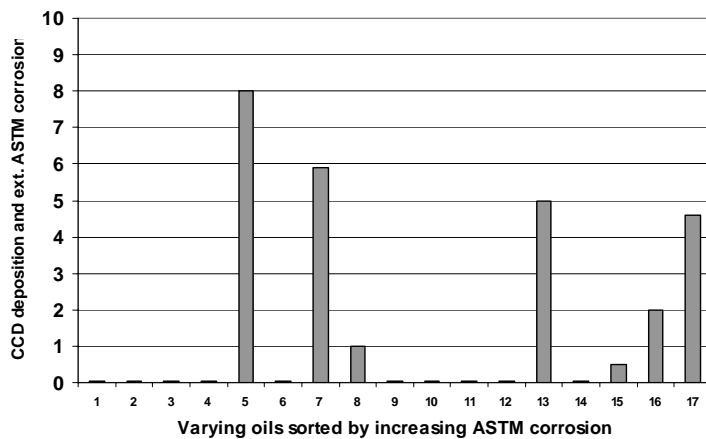


Fig. 9 Results from CCD test of selected group of commercial transformer oils

3.3 Correlation and evaluation of extended ASTM and CCD test methods

When the results from the two test methods are compared it is evident that the correlation between the two test methods is poor, and no apparent relation seems to exist between the two. Clearly the two methods do not measure the same property of the oils, and they forecast very differently which oils should be avoided.

In order to evaluate the test methods, we need to compare the result to the real service performance of the oils tested. The following service record is known to us about these oils:

1. **Failure group:** Oils number 7, 13, 16, and 17 are confirmed to have been involved in Cu_2S -deposition failures of transformers.
2. **No- Failure group:** No oil in this group is known to have caused any Cu_2S - deposition failures
3. **New oil:** Oil number 5 is relatively recently available on the market with very short service time and therefore has no real service record yet, so it cannot really be used to evaluate the methods

Extended ASTM: With the commonly used D130 criterion (<4) the extended ASTM method was not able to separate out any of the oils in the failure group. With a tougher criterion (<3) the complete group 9-17 would have to be disqualified. In this group then failure- oils 13, 16 and 17 would have been removed, but also oils in the No- failure group 2. Further oil number 7 in the failure group would still have passed. Clearly, the extended ASTM method cannot selectively identify depositing oils.

CCD: With pass criterion deposition “1 or less”, the CCD test would screen out oils number 7, 13, 16 and 17 as clearly depositing, and 8 as borderline. Hence all the confirmed depositing oils in the failure group1 (oils 7, 13, 16, and 17) were correctly identified by the CCD method, whereas the No- failure oil number 8 was on the borderline. If the pass criterion instead is set as “2 or less” the method correctly screens out exactly the known failure oils.

Our conclusion from this comparison is that the CCD based method appears to be a superior and very selective method for identifying oils known to have caused failures in real service, and is hence a very promising candidate for a future corrosion test

3.4 Conclusions regarding oil corrosivity test methods

The experimental observation of the pronounced oxygen dependence of the oil corrosion reactions and subsequent Cu_2S deposition suggests that oil corrosivity tests should be performed under some type of controlled oxygen presence. This is clearly demonstrated in the comparison of the Extended ASTM versus CCD methods.

BIBLIOGRAPHY

- [1] J. Hajek, M. Dahlund, L. Pettersson, "Quality of oil makes the difference, ABB discovers the solution to transformer breakdowns", ABB Review, Nr. 3-2004 pp.61-63
- [2] Lewand, L.R. "Investigating copper sulphide contamination in a failed large GSU transformer", Proceedings of the Annual International Conference of Doble Clients, Boston, MA, 2005
- [3] C. Bengtsson et al., "Oil Corrosion and Cu₂S Deposition in Power Transformers", CIGRE Moscow Symposium 2005
- [4] ABINEE, Workshop on Corrosive Sulphur in Oil, June 2-3 2005, Sao Paulo, Brasil: presentations by Areva, ABB, Doble, Nynas, Siemens, Toshiba, Terna; on internet: <http://www.abinee.org.br/anexo/enxofre1.exe>, <http://www.abinee.org.br/anexo/enxofre2.exe>, <http://www.abinee.org.br/anexo/enxofre3.exe>
- [5] IEEE/PES Transformer Committee: "Tutorial on Corrosive Sulfur" available on internet: <http://grouper.ieee.org/groups/transformers/info/F05/F05-CorrosiveSulfurPresentation.pdf>
- [6] Rocha, A.H. "Faults in 500-kV shunt Reactors Caused by Corrosive Sulfur in the Insulating Oil", Proc. of the Sixty-Eight Annual Int'l Conference of Doble Clients, Boston, MA, 2001, Sec. 5-4.
- [7] Oommen, T.V. "Corrosive and Non-corrosive Sulfur in Transformer Oils", Electrical/Electronics Insulation Conference, Chicago, October 4-7, 1993.
- [8] Lewand, L.R. "The Role of Corrosive Sulfur in Transformers and Transformer Oil", Proc. of the Sixty-Ninth Annual Int'l Conference of Doble Clients, Insulating Materials Session, 2002.
- [9] ASTM D1275-03, "Standard Test Method for Corrosive Sulfur in Electrical Insulating Oils", Volume 10.03, ASTM International, 2003.
- [10] DIN 51353: Testing of Insulating Oils, Detection of Corrosive Sulfur, Silver Strip Method, Auslandsnormenvermittlung im DIN, Burggrafenstrabe 6, D-1000 Berlin 30, Germany, 1985
- [11] Clair Claiborne, Mats Dahlund, Karin Gustafsson, Jan Hajek, Arne Hjortsberg, "Specification and testing of transformer oils with respect to corrosion", Proceedings of the Annual International Conference of Doble Clients, Boston, MA, 2005.
- [12] CIGRE Task force A2-31 report "Copper sulphide in transformer insulation", Elektra, 2006
- [13] IEC TC10 has set up a WG (35) to study in conjunction with CIGRE a new adequate test method, "Detection of potentially corrosive sulphur in mineral oil" with scope to develop a test method for the evaluation of the corrosive sulphur behaviour of used and unused mineral insulating oils.
- [14] G. M. Bastos, J. C. Brandão, J. Santelli, R. Albuquerque, J.C.Mendes, J. Hajek: "HVDC converter transformer performance on Itaipu system", CIGRE, Paris 2006.